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ELECTRON GUN TECHNOLOGY

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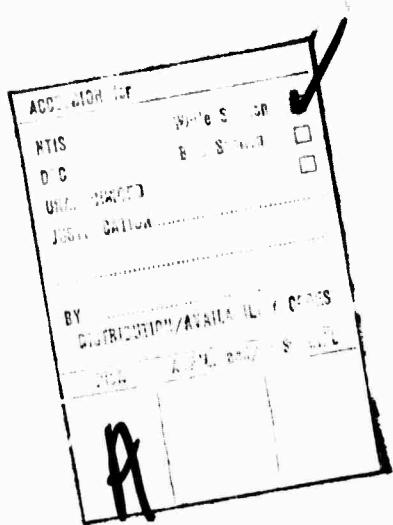
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shown that the plasma cathode e-gun is capable of producing large scale e-beams (demonstrated 1000 cm^2) at 150 keV and with a cw current density of 1 mA/cm^2 extracted through a thin foil window.

59 cm

Within this reporting period the development of a new ion plasma electron gun has begun. In this gun, a low pressure, thin wire discharge produces ions which are accelerated to collide with the cathode. Secondary electrons are emitted at the cathode and they are accelerated by the same high voltage and extracted through a foil window. Potential advantages of this gun include high voltage operation (400 kV), high output current density (1 to 3 A/cm^2), pulsed and cw operation, dc high voltage power supply for repetitively pulsed operation, no control electronics floating at high voltage, mono-energetic e-beam, and scalability.

An ion plasma e-gun with an aperture of $4 \text{ cm} \times 40 \text{ cm}$ has produced a beam with an energy of 120 keV and with a maximum output current density of greater than 360 mA/cm^2 in a $5 \mu\text{sec}$ FWHM pulse. Operation with current pulse lengths up to 150 msec has also been obtained. Preliminary measurements of the extracted e-beam uniformity have been taken.

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I. INTRODUCTION

During previous reporting periods of this contract (N00014-72-C-0496), the plasma cathode electron gun has been developed to a point where practical, operating, large scale electron guns have been built for various applications. Both the cw and the pulsed operation of these guns has been characterized. During this reporting period (January through June 1976), a new electron gun, the ion plasma electron gun was built and tested. This ion plasma electron gun, called the plasma anode electron gun in the previous contract report (Semiannual Technical Report No. 7) is a new Hughes invention which was first reduced to practice at the Hughes Culver City facility on company IR&D funds. On the present program the ion plasma e-gun has been operated at beam voltages up to 120 kV, at current pulse widths from 5 μ sec to 150 msec, and measurements taken of the gun efficiency, extracted output current density, and output beam uniformity. A maximum average output cathode current density of 360 mA/cm² has been obtained.

In this report, the principles of operation of the ion plasma electron gun will be described in Section II. Section III presents the experimental results obtained, and Section IV contains a summary of the conclusions of the results from this reporting period.

II. THE ION PLASMA ELECTRON GUN

The ion plasma electron gun is a new type of electron gun which is capable of operation at lower gas pressures than most other gas-filled guns. This lower pressure means that the ion plasma e-gun is capable of the high voltage operation and high current fluxes applicable to e-beam sustained laser systems in pulsed and cw operation.

A. Theory of Operation

A schematic of the ion plasma electron gun is shown in Figure 1. In this gun a low voltage plasma is struck near the anode and this plasma acts as a source of ions. This plasma may be obtained by any one of the several means including a thermionic diode discharge, a hollow cathode discharge, or a thin wire discharge. The thin wire discharge is the method shown schematically in Figure 1 and will be described more fully below. A fraction of the ions produced in the discharge are accelerated to the cathode (negative high voltage of as much as 400 kV) where they collide with the electrode surface and produce secondary electrons. These electrons, then, are accelerated back toward the anode, experiencing few collisions in the process of passing through the low pressure gas (mean free path for 100 kV electrons in 20 mTorr of helium is ≈ 100 meters¹). This beam of electrons then passes through the thin foil window and into the laser chamber or region where the beam is to be utilized.

A prediction of the output current density and the efficiency of the ion plasma e-gun requires values for the fraction of ions in the discharge plasma extracted through the grid into the acceleration region, and the secondary electron emission coefficient for the high energy ions striking the cathode surface. Although exact values of these parameters are not available at this time, an estimate may be made. In a plasma the random plasma current is given by

$$J_p = \frac{ne\langle v \rangle}{4}$$

where n = plasma density, e = electronic charge (singly ionized species), and $\langle v \rangle$ = average velocity.

For a plasma discharge region which has a square cross section and is much longer than the transverse dimension, the random plasma ion current impinging on the grid can be shown to be equal to thin wire current, I_D . The amount of this random ion current which passes through the grid will depend upon the grid transmission, η_g . The decrease in ion current due to interception by this grid may be assumed to be made up for by the increased ion current passing through the grid due to the penetration of the large accelerating field into the discharge region. This means that the ion current traveling to the cathode $I_+ \approx I_D$. McClure² has studied high voltage glow discharges in D_2 gas and has measured the secondary emission coefficient of D_2^+ ions, at 60 kV on stainless steel to be ≈ 10 . Earlier studies of secondary emission due to >100 keV He^+ ions on molybdenum indicated a value of 10-14 for the secondary emission coefficient.³ Using a value of ten for the secondary emission coefficient means, then, that the electron current, I_- , in the acceleration region, will be $I_- \approx 10 I_D$ and that the amount passing through the foil will become $I_e \approx 10 \eta_g \eta_f I_D$ where

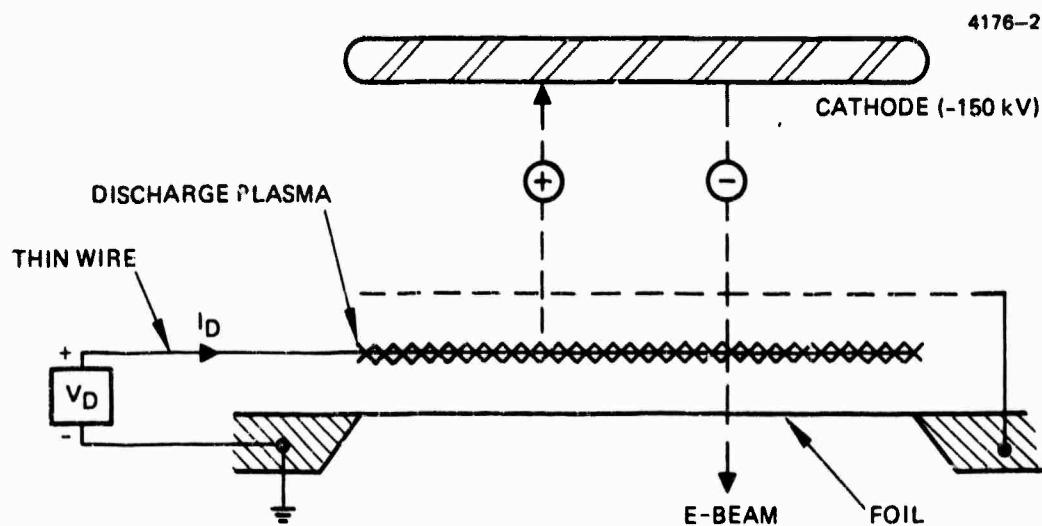


Figure 1. Ion plasma electron gun schematic.

η_g = particle transmission of the grid

η_f = foil and foil structure particle transmission.

At beam voltages in excess of 150 kV, $I_e \approx 5-7 I_D$ should be obtainable.

The energy deposited into the plasma is small compared to that drawn from the high voltage supply (the plasma voltage is ≈ 400 V). Because of this, the gun efficiency depends on the ratio of the energy delivered by the high voltage supply to the electrons compared to the total that is delivered to the ions and electrons and will be $\approx 10/11 \times \eta_g \eta_f'$. In this expression η_f' is the energy transmission of the foil and structure (the energy and particle transmission through a foil are different). At high beam voltages this efficiency should be around 50 to 60%.

As mentioned above there are several ways to produce the discharge plasma which acts as the source of ions. Of these possibilities, the thin wire discharge operates at a low pressure compatible with high voltage operation of the gun and may be utilized with a compact design configuration. The thin wire discharge, which has been experimentally studied¹, McClure,⁴ can operate at low pressure because the thin wire permits highly efficient electrostatic trapping of electrons to sustain the discharge. In this discharge, electrons are trapped in the electric field near the thin wire (at a positive voltage of ≈ 400 V) and form helical orbits around the wire. The formation of these orbits allows the electron to attain long path lengths so that ionization of helium atoms can occur (ionization mean free path in 10 mTorr of helium for 100 eV electrons is ≈ 70 cm¹). By this mechanism a limited sustaining generation of electrons is obtained. In the present experiments this thin wire discharge has been operated with pressures as low as 2 mTorr in helium.

In the ion plasma electron gun an array of thin wires, each wire separately driven, may be distributed across the beam aperture and in the discharge region. The depth of the discharge region may be as small as a centimeter so that this does not add much to the size of the gun. The use of a hollow cathode discharge is also an efficient ion source, but for operation at pressures ≤ 10 mTorr the ratio of the

surface area of the hollow cathode to the extraction area must be about 100. This large area ratio increases the size of the gun. The use of a thermionic cathode discharge as an ion source allows operation at low pressure, but again a significant increase in size must occur to accommodate the cathode heaters.

The ion plasma electron gun, as described above, has important potential advantages for application to e-beam pumped laser systems. These advantages include:

1. **High Voltage Operation:** Because the ion plasma e-gun can operate with a helium gas pressure below 10 mTorr, operation with a beam voltage in excess of 400 kV may be anticipated.
2. **High Current Density:** A current density of between 1 and 3 A/cm² may be estimated for beam voltages of 300 kV or higher. The maximum current density obtainable may be limited by space charge effects on the ion beam being extracted from the discharge region.
3. **CW and Pulsed Operation:** As will be described below, the ion plasma e-gun has operated both cw and in the pulsed mode with pulse lengths as short as 0.5 μ sec. Unlike the cold cathode field effect guns, the output current density does not fall with increasing pulse length due to limitations of the gun mechanism. Instead, the average currents obtainable are set by foil window cooling and power supply limitations.
4. **Monoenergetic Beam:** Even at high ion energies, secondary electrons emitted are expected to have initial energies less than 40 eV.^{3,5} At the high beam energies anticipated, this represents a small fractional energy spread. Because of this, and the fact that a dc high voltage supply is used, a very monoenergetic e-beam may be expected which will result in good foil penetration. Low energy electrons, resulting from the rise and fall of the supply voltage, present with field-effect cold-cathode guns will not be present with the ion plasma e-gun.
5. **Gun Control with Electronics at Ground Potential:** The ion plasma gun is controlled by the plasma discharge which operates at about 400 V above the ground electrode (anode) of the gun. This means there is no need for electronics to run the gun to be floated at high voltage which is necessary with thermionic e-guns and the plasma cathode e-gun.

6. DC High Voltage Supply for Repetitively Pulsed Operation: For applications requiring repetitively pulsed operation, the ion plasma gun will operate with a dc high voltage supply. Field effect e-guns require a repetitively pulsed Marx-bank high voltage supply.
7. Scalable: Based on experience on this program with the wire discharge, there appears to be no reason why the ion plasma gun cannot be scaled to produce large area beams.

B. Previous Results

The ion plasma electron gun was first reduced to practice at the Hughes Aircraft Company facility in Culver City on company IR&D funds. The configuration of this gun is schematically indicated in Figure 2. In this gun the source of ions is the hollow cathode discharge for which V_D , the discharge voltage varies from 100 to 700 V depending on the helium pressure. The control grid is operated at a positive potential $\geq V_D$ and serves to control the e-beam by controlling the transmission of ions to the cathode. In other respects this gun can be seen to be similar to the general ion plasma gun shown in Figure 1. In operation a 5 cm x 20 cm electron beam was extracted through a (0.0005 in.) aluminum foil window with a beam voltage of 90 kV. In cw operation (5 sec run time) a beam current density of 0.5 mA/cm^2 was measured and a pulsed current density of 100 mA/cm^2 was obtained in a 0.5 to 1 μsec FWHM pulse.

Concurrently, Pigache and Fournier⁶ developed and published the results of an ion plasma e-gun which they called the secondary emission electron gun. In their gun a thermionic diode discharge was used as the ion source and an 80 μsec FWHM pulsed e-beam at 130 kV with dimensions of 5 cm x 15 cm was extracted. The maximum current density obtained with this gun was reported to be about 1 mA/cm^2 .

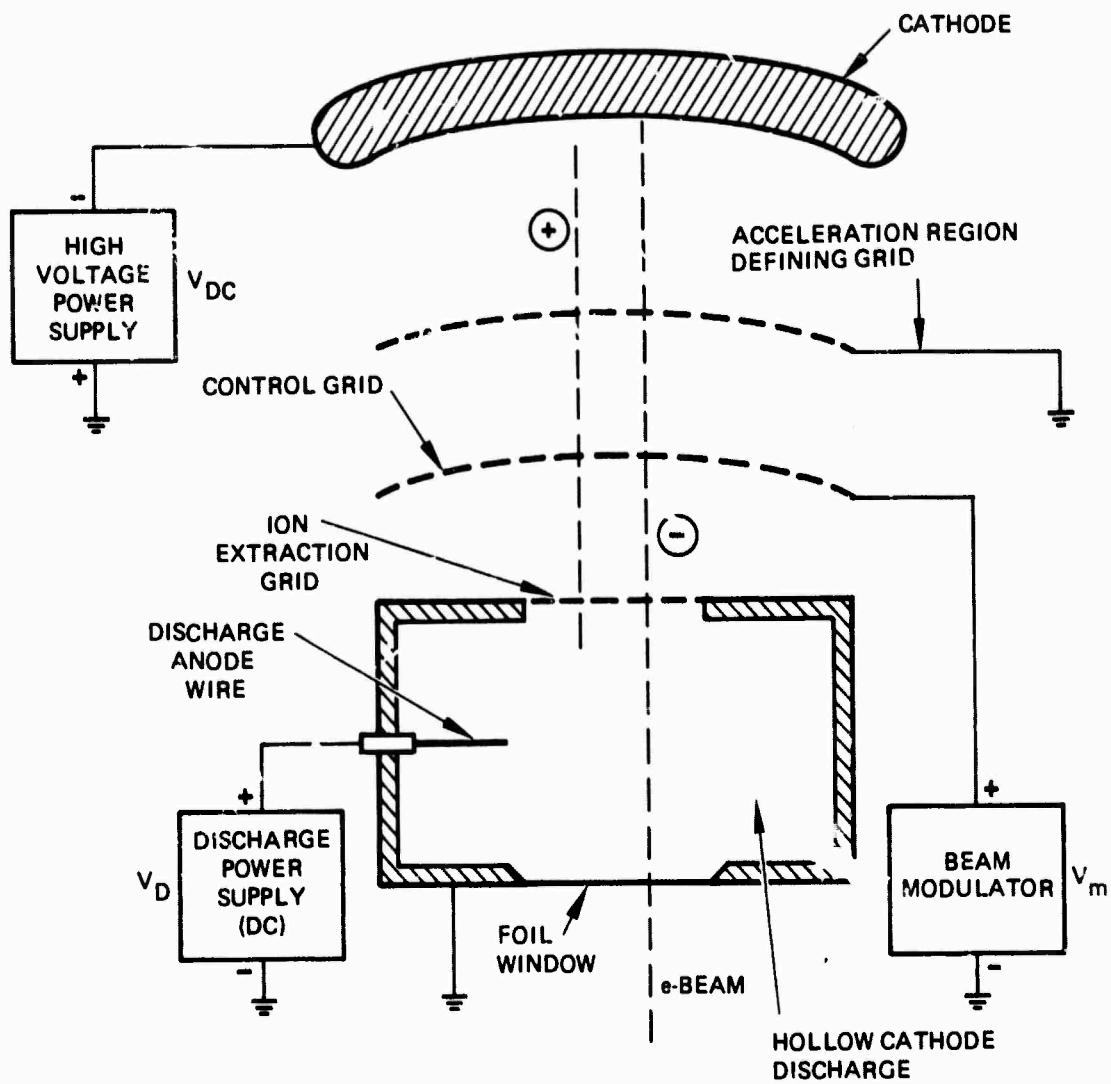


Fig. 2. Schematic representation of the 5 cm x 20 cm aperture ion plasma electron gun, utilizing a hollow cathode discharge as the ion source, which was built and operated at Hughes Aircraft Company at Culver City.

III. DESCRIPTION AND RESULTS OF EXPERIMENTS

Initial experiments to test and characterize the ion plasma electron gun have been carried out utilizing a modified, plasma cathode electron gun with a 4 cm x 40 cm aperture. The ion plasma gun which resulted from these modifications is not an optimum design, but it is a flexible test vehicle capable of operation up to 150 kV which was inexpensive to make into its present configuration.

A. Experimental Arrangement

A schematic representation of the test device ion plasma electron gun is shown in Figure 3. In the gun, the high voltage acceleration region is defined by the flat portion of the cathode surface and a mesh grid at the plasma generation region, a gap spacing of 4 cm. The plasma generation region is a thin wire discharge chamber with a 4 cm x 4 cm transverse cross section in which seven individual 0.3 mm diameter tungsten thin-wire discharges may be run. The layout of these wires is indicated in Figure 4. The four wires running transversely across the region are located 1.6 mm below the plane containing the three longitudinal wires. Although it was possible to run all seven wires individually, with separately controlled currents, in the data taken so far only the three longitudinal wires were used and the transverse wires were, on occasion, used as Langmuir probes. The foil support structure included a mesh grid resting on an aluminum plate with slots milled in it. The foil window pressed against the other side of the slotted aluminum plate. This configuration provides a 50% electron transmission. In these experiments, a foil window of 0.025 mm thick (0.001 in.) aluminum was used. Other than the components noted differently above, the metallic parts of the gun were fabricated from stainless steel.

This gun was mounted to a plexiglas diagnostics box which could be evacuated to less than 10 mTorr so that probe measurements of the transmitted e-beam could be made without complications from the scattering and production of electrons from collisions with gas

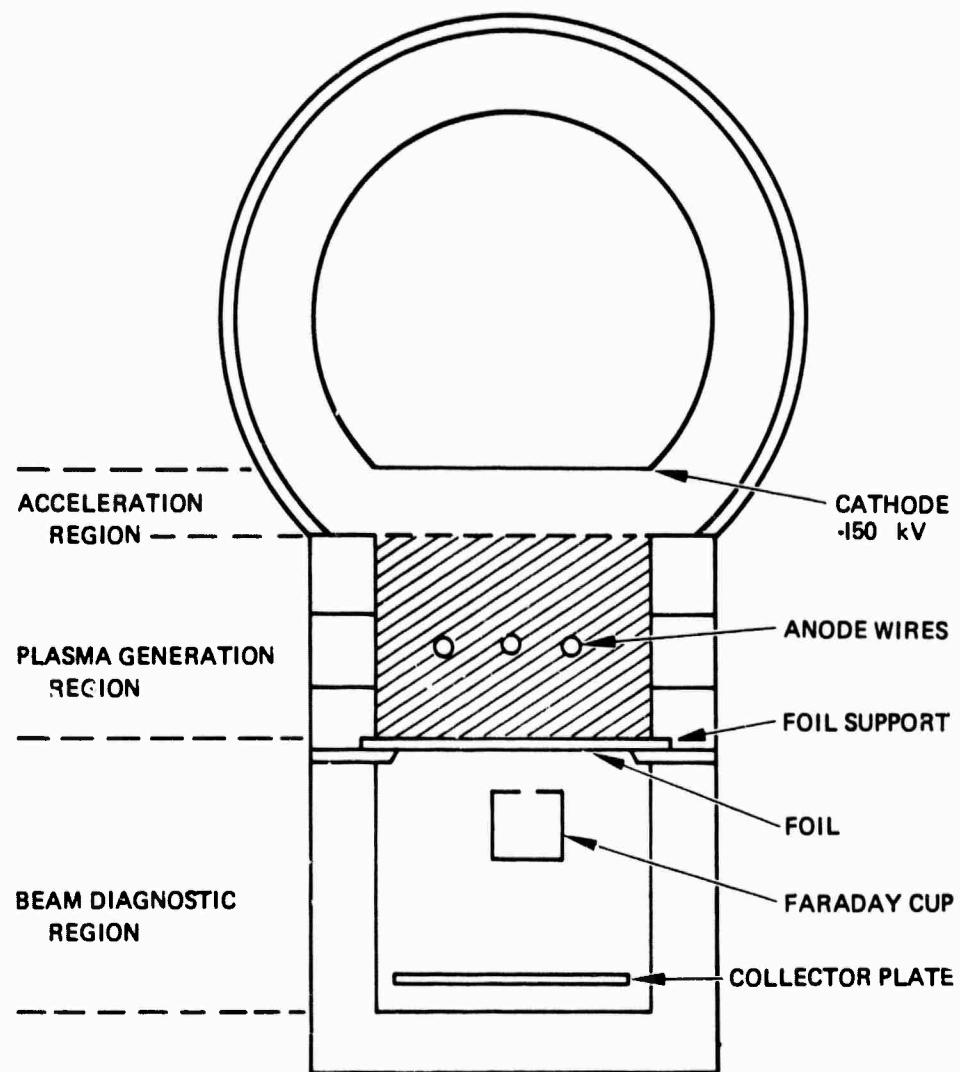


Figure 3. Ion plasma e-gun test device.

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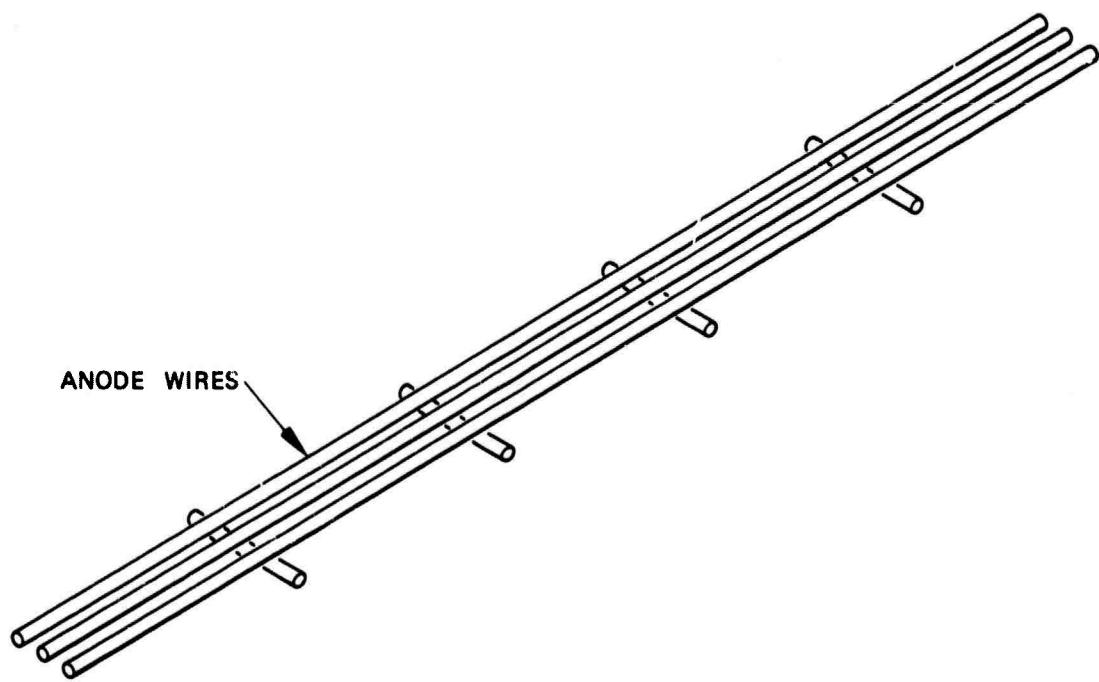


Figure 4. Perspective view of the alignment of the thin anode wires.

molecules. In the diagnostic box there were two different current collectors to measure the e-beam transmitted through the foil. The first of these, located just downstream of the foil, is a 6.35 mm diameter Faraday cup probe which may be positioned at any point within the 4 cm x 40 cm e-beam aperture. The Faraday cup consists of a solid plate placed behind a retarding screen which may be biased to eliminate the effects of secondary emission from influencing the measured current in the probe. This probe is used to take data on the spatial uniformity of the extracted e-beam. A solid, 6 cm x 45 cm aluminum collector plate which collects (approximately) the total transmitted e-beam is located behind the moving Faraday cup probe. The diagnostics box, including the moving probe and collector plate, is shown in Figure 5.

The ion plasma electron gun was operated in two different modes: a quasi-cw mode of operation in which the thin wire anode discharges were switched on for 5 to 150 msec and a fast pulse mode yielding anode wire current pulses of approximately 5 μ sec FWHM. In the first case, the quasi-cw operation, for which the test schematic is given in Figure 6, the length of time for the current output to remain on was determined by the energy storage capacity of the high voltage power supply and the associated circuitry. Care was also taken in this mode of operation to insure that the three anode wires carried equal currents. In short pulse operation a 0.01 μ F capacitor charged to 2 kV was switched across the thin-wire discharge (all three wires together, in parallel) by means of a thyratron. In this case no attempt was made to insure or ascertain the equality of the thin-wire currents.

B. Experimental Results

During each experiment each of the following currents were monitored with the method described.

1. Total Cathode Current

This current, which is the sum of the ion current impinging on and the electron current leaving (due to secondary emission) the cathode was read using a Pearson current transformer and an

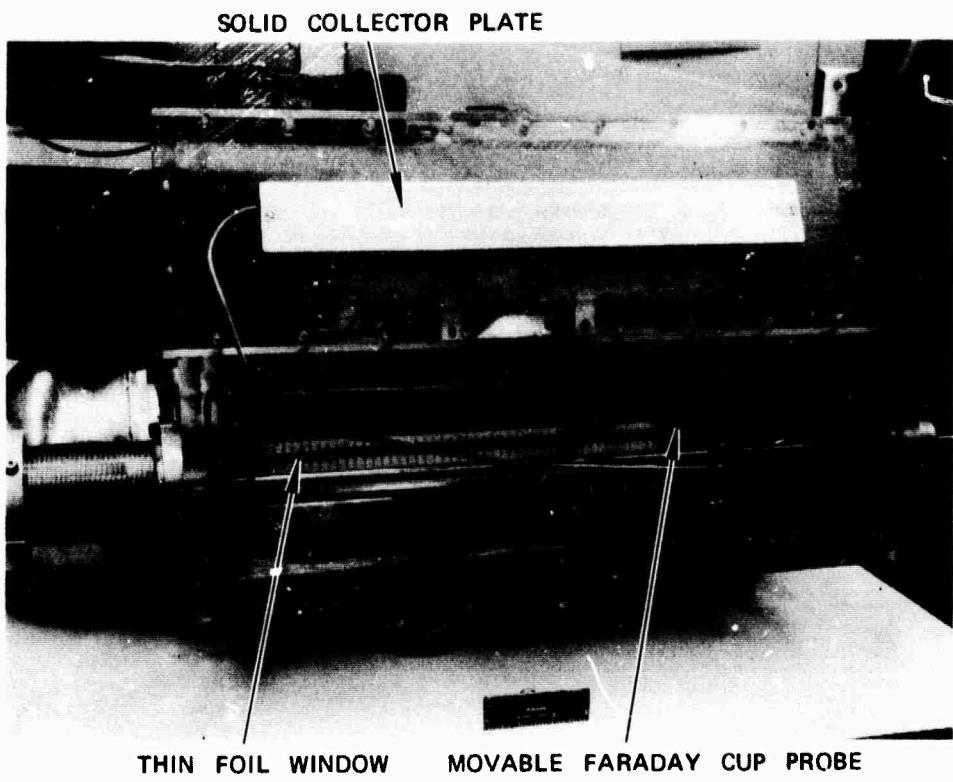


Figure 5. The diagnostics chamber.

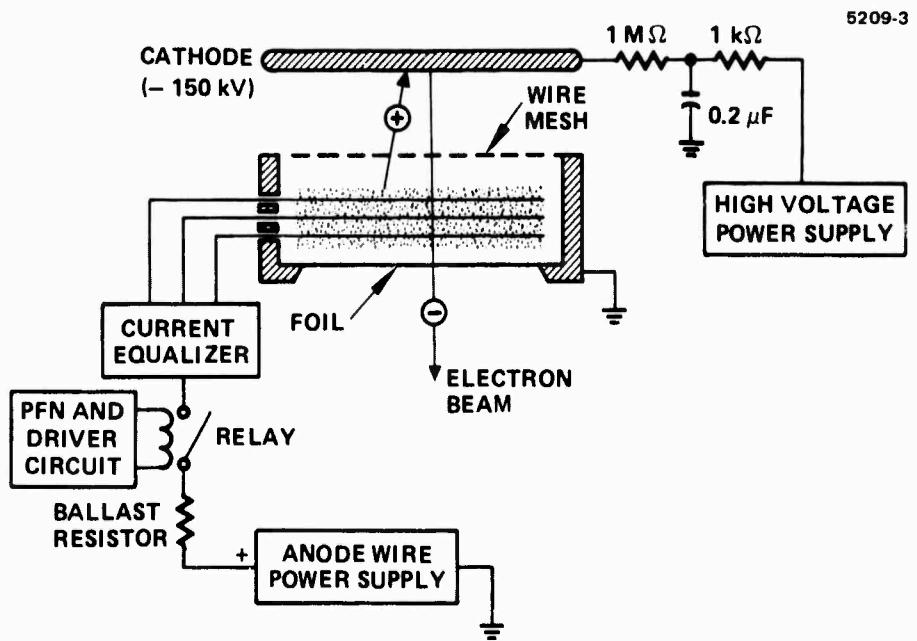


Figure 6. Ion plasma e-gun test schematic for quasi-cw operation.

oscilloscope readout. The current transformer was placed around a portion of the RG19 high voltage cable, with the outer conductor removed, which connected the high voltage supply to the cathode of the gun.

2. Total Thin-Wire Current

The sum of the currents in the three longitudinal thin-wire discharges was also monitored via a Pearson current transformer.

3. Faraday Cup Probe Current

For the quasi-dc current measurements, this current was small so that the voltage drop across a $10\ \Omega$ resistor, placed between the cup and ground, was read and amplified (gain, 10^3) for display on an oscilloscope. For the short pulsed measurements, a Pearson current transformer could be used. The Faraday cup collector was run at +10 V to help eliminate the effects of secondary emission. Even so, the collected current read in such an arrangement has been estimated to be about 25% less than the actual e-beam current entering the cup aperture.⁶ The amplifier-display system was carefully calibrated.

4. Collector Plate Current

Apart from the e-beam current collected by the Faraday cup, this current represents the total transmitted e-beam and was read via a Pearson current transformer in the ground return lead. The collector plate was not biased.

In typical experiments run at a 110 kV beam current, the ratio of the collector plate current to the total cathode current was found to be ≈ 0.05 . Factors contributing to this ratio are

- a. Fraction of the total cathode current which is electron current ≈ 0.91 for a secondary emission coefficient of 10 at the cathode.
- b. Two screen mesh grids, above and below the plasma discharge region, each with a transmission of 0.62 for a total transmission of 0.38.

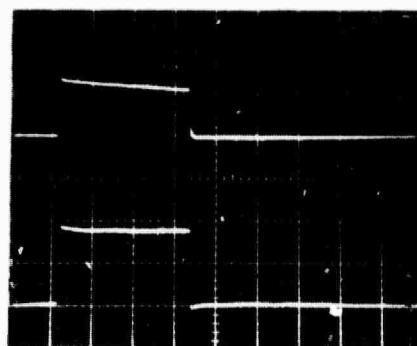
- c. Foil support transmission of 0.8.
- d. Foil window transmission of ≈ 0.7 .
- e. Reflection of electrons and secondary emission of electrons at the collector plate of ≈ 0.5 .
- f. Shadowing due to the Faraday cup and its support (usually positioned in the center of the beam) is 0.72.

The product of these factors yields a ratio of ~ 0.07 . This value is larger than that which is observed, but since the collector plate is located 20 cm from the foil, scattering of electrons coming through the foil could cause them to miss the plate and account for the difference.

The ratio of the cathode current to the anode thin-wire current was found to be a constant value around six for the long pulse operation. With a secondary emission coefficient of 10 and the model presented in Section II for the thin-wire discharge, this ratio would be ≈ 11 . Because of the speculative nature of both the model and the assumed value for the secondary emission, such a difference in the two values is not surprising. The relationship between the two currents for short pulse operation was considerably different than for the long pulse case. This fact will be discussed below.

Figure 7 shows an oscillogram of the current waveforms for the total thin-wire anode current and the total cathode current for an 8 msec pulse length. The droop of the anode wire current waveform is due to the characteristics of the Pearson Model 2100 current transformer used for that measurements. Figure 8 shows waveforms for the same two currents for a 5 μ sec FWHM current pulse. Here it may be seen that the cathode current has a long ($\approx 40 \mu$ sec) fall time, which may be due to reasons similar to that previously observed in this kind of gun⁶ but which is most likely a circuit effect due to cable capacitance in the present case.

In Figure 9 the total cathode current and the average cathode current flux (i.e., the total cathode current divided by the gun aperture area of 160 cm^2) are shown as a function of the total anode wire current. It may be seen that the relationship between the two currents for the



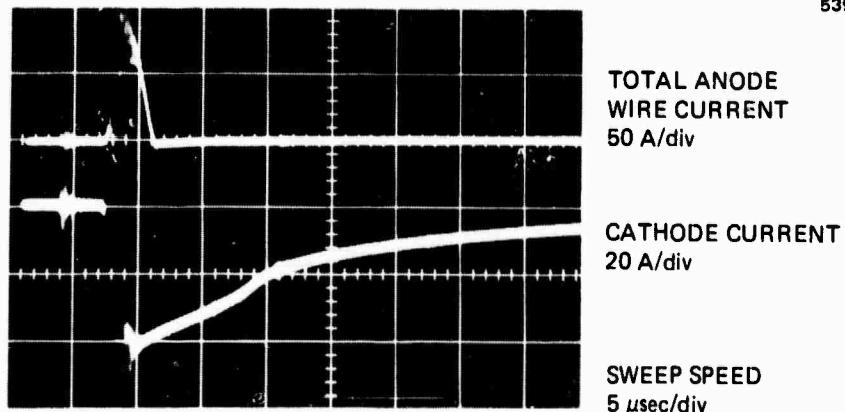
TOTAL ANODE
WIRE CURRENT
50 mA/div

CATHODE CURRENT
0.5 A/div

SWEEP SPEED
2 msec/div

Fig. 7.

Anode wire and cathode output current for the ion plasma electron gun at 110 kV beam voltage and with quasi-cw (long pulse) operation.



TOTAL ANODE
WIRE CURRENT
50 A/div

CATHODE CURRENT
20 A/div

SWEEP SPEED
5 μsec/div

Fig. 8.

Anode wire and cathode output current for the ion plasma electron gun at 110 kV beam voltage with short pulse operation.

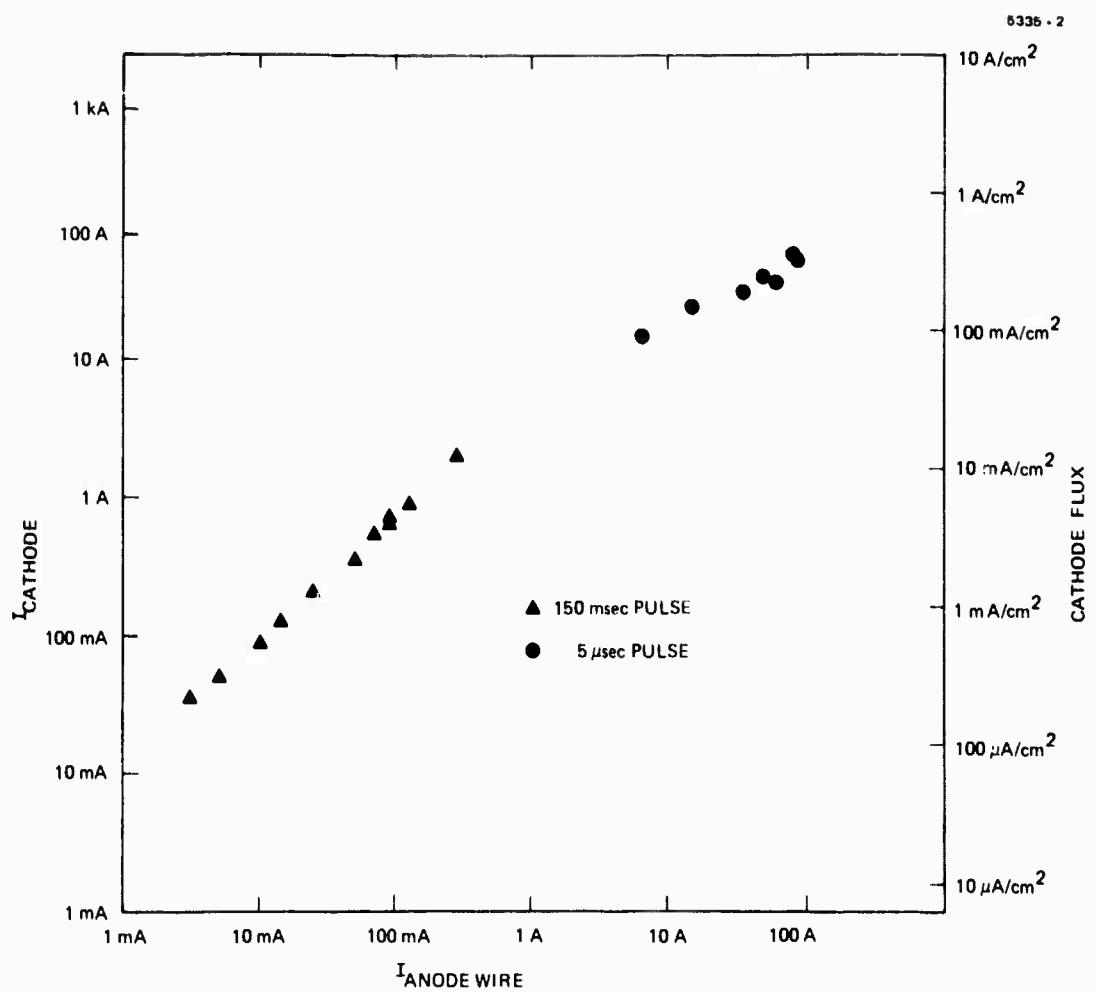


Fig. 9. Cathode current output of the ion plasma electron gun as a function of anode current input, beam voltage is 110 kV.

higher current, short pulse cases is much different than for low currents, longer pulse operation. A least squares fit to the data at high currents gives

$$I_{\text{cathode}} \approx 5.9 (I_{\text{anode}})^{0.50} \cdot (\text{short pulse})$$

as compared with

$$I_{\text{cathode}} \approx 5.8 I_{\text{anode}} \cdot (\text{long pulse}) .$$

Possible reasons for the change from a linear to a square root dependence of the currents include (1) the onset of space charge effects which would limit the ion current density which could be extracted from the discharge into the acceleration region and (2) inductance of the thin wires which, for short pulses could cause the current to be bunched rather than distributed uniformly along the wire. If space charge is the cause of the different current relationship, it would be expected that the functional dependence of output current on anode current should further saturate as the space charge limited value of current is approached. Since, in the present case, the current relationship for short pulses extends over a decade of anode current variation, and because the maximum cathode current of 360 mA/cm^2 is over 50% of the space charge limited value (assuming a secondary emission coefficient of 10), some inductance effect is probably indicated. This short pulse current relationship is still being studied. A new array of shorter, transverse, anode wires is being installed which will allow the short pulse current to be increased an order of magnitude and with much lower system inductance. In addition, the moving Faraday cup is being modified so that the spatial distribution of the extracted current density may be studied for the short current pulses.

Preliminary results on the uniformity of the output current density were taken with the movable Faraday cup for positions along the longitudinal axis of the beam aperture. Two scans of 21 points along the axis were taken at two different values of the cathode current as shown in Figure 10. For each data point a separate current pulse

of the gun was extracted and the shot to shot repeatability of similar pulses with the Faraday cup in a single position was found to be between 10 and 15%. For the data shown, if account is taken of the uncertainty of ≈ 10 to 15% of each point, it may be concluded that the output uniformity of the gun will probably prove to be very good within the central 30 cm of the 40 cm long aperture. Finally, it may be noted, that the value of current density read by the Faraday cup probe when positioned in the middle of the aperture would lead to a 2 to 3 times larger value of the total collector plate current than is actually read. This fact corroborates the earlier statement that secondary emission and reflection at the plate, as well as scattering of the e-beam from the foil causing electrons to miss the plate, accounts for the lower than expected readings of collector plate current.

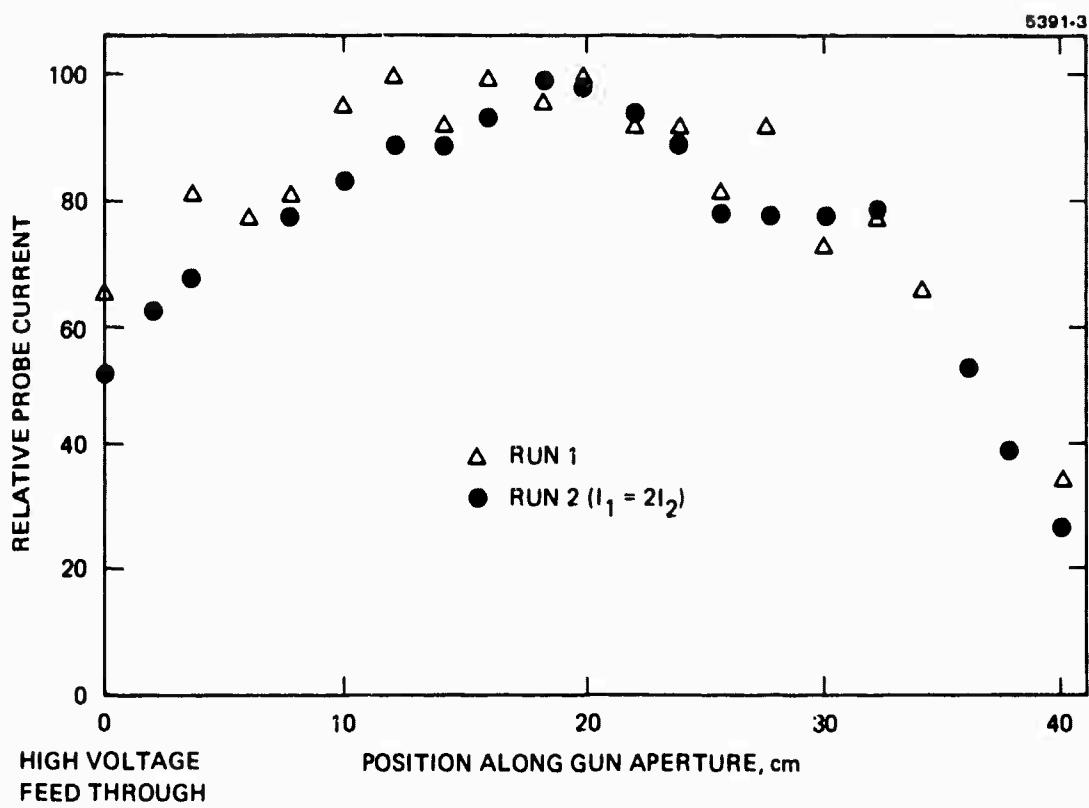


Fig. 10. Uniformity of the output current density as read by the movable Faraday cup for 8 msec current pulses.

IV. CONCLUSIONS

Preliminary experiments on a 4 cm x 40 cm ion plasma electron gun have been conducted. In these experiments the following operating parameters have been found:

1. Beam Voltage: Up to 120 kV. Higher beam voltages have not been attempted due to problems with the high voltage power supply. The gun itself operates in a very stable manner with very few arcing, corona, or other high voltage breakdown problems. When the power supply difficulties are corrected, the beam voltage will be raised to 160 kV, the limits of the energy storage capacitors.
2. Pulse Length: 5 μ sec to 150 msec. At the shorter pulse lengths, 5 to 10 μ sec FWHM, large currents could be drawn from the gun. At the long pulse lengths 1 to 150 msec, the gun operated in a cw-type manner in that there was no change in output characteristics over the entire range of pulse duration except for limitations due to the energy capacity of the power supplies. This fact suggests that these operating times are longer than any transient effects in the gun and that operation is essentially steady state.
3. Output Current: Maximum of 65 A cathode current which implies a current density greater than 360 mA/cm^2 . This value of current density was obtained in a 5 μ sec pulse length. In the cw-type, long pulse operation a maximum output current of 2A ($>10 \text{ mA/cm}^2$) was obtained. The ultimate maximum output current density

obtainable from the ion plasma e-gun will be due to the space charge limit imposed by the ions. The exact value of this maximum current density cannot be predicted due to uncertainty in knowing the secondary electron emission coefficient of the cathode and because there may be partial charge neutralization the ion field in the region of the ion extraction grid. In the present gun it is estimated that as much as 50% of the space charge limited value of current density has been obtained.

4. Pressure: Typically 10 to 15 mTorr of helium. In the short-pulse operation the gun pressure could be lowered to 2 mTorr. At these pressures, the ion plasma gun could be operated at beam voltages limited mainly by vacuum breakdown and not by Paschen breakdown for up to ~400 kV.

In the cw-type of operation the spatial uniformity of the output current, density was measured by means of a moving Faraday cup located downstream of a 0.001 in. thick aluminum foil window. The results of this experiment, based on only two sets of data for different sets of operating parameters, show that the ion plasma gun gives a beam with good uniformity except for regions just near the edges of the aperture. Within the central portion of the gun aperture, no hot spots nor pronounced current minima are observed.

The test configuration of the gun is being modified for future experiments. A new anode wire array is being installed which will decrease the system inductance (for short pulse operation) and allow an order of magnitude increase in the total anode wire current to be obtained. In addition, the circuitry is being modified so that the moving Faraday cup may be used in the short pulse experiments to study the uniformity of the output current density.

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